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Count-Rate Performance of the Discovery STE PET Scanner Using Partial Collimation

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Abstract

We investigated the use of partial collimation on a clinical PET scanner by removing septa from conventional 2D collimators. The goal is to improve noise equivalent count-rates (NEC) compared to 2D and 3D scans for clinically relevant activity concentrations. We evaluated two cases: removing half of the septa (2.5D); and removing two-thirds of the septa (2.7D). System performance was first modeled using the SimSET simulation package, and then measured with the NEMA NU2-2001 count-rate cylinder (20 cm dia., 70 cm long), and 27 cm and 35 cm diameter cylinders of the same length. An image quality phantom was also imaged with the 2.7D collimator. SimSET predicted the relative NEC curves very well, as confirmed by measurements, with 2.5D and 2.7D NEC greater than 2D and 3D NEC in the range of ~5–20 mCi in the phantom. We successfully reconstructed images of the image quality phantom from measured 2.7D data using custom 2.7D normalization. Partial collimation shows promise for optimized clinical imaging in a fixed-collimator system.

I. Introduction

The clinical use of fully 3D mode positron emission tomography (PET) has demonstrated advantages over 2D mode in brain imaging [1]. The advantages of 3D mode for whole body scanning are less established [2] – [4]. We investigated acquisition modes with an

intermediate number of septa between conventional 2D and 3D modes on the Discovery STE PET scanner (GE Healthcare Technologies). This work focused on the noise equivalent count-rate (NEC) metric, which is used to compare the statistical quality of global count rates from PET scanners [5]. NEC is computed from the true (T), random (R), and scattered (S) coincidence counts as:

$$NEC = T^2 / (T + S + R)$$

Randoms and deadtime effects limit NEC in 3D mode – the system is overloaded with typical clinical activity levels within the field of view. The NEC is limited by collimation in 2D mode – the system never reaches its count rate potential with clinical activity levels. The goal of using the partial collimation configuration is to improve the statistically relevant count rates over 2D and fully 3D configurations for clinical activity concentrations and patient sizes.

Extensive work has been done to optimize collimators for SPECT imaging (e.g. Moore et al. [6]). Less attention has been paid to the septa used in PET image acquisitions. Most of the previous work on partial collimation systems concerns hybrid PET systems e.g. [7], [8] where axial slats were investigated as a means of reducing random coincidences. For full ring PET scanners, Aykac et al. [9] evaluated different septa designs in conjunction with a modification of their prototype high-resolution PET scanner, using NEC as a figure merit. They then followed up with a detectability study for brain lesions [10], finding a definitive increase in NEC rates, but questionable improvement in detectability. More recently, Hasegawa et al. have proposed, constructed, and evaluated [11] – [12] a long bore PET scanner with septa located between detector blocks, rather than between every ring of detector crystals. Qi et al. [13] have used simulations to systematically evaluate both the NEC and the task based performance of lesion detection for a prostate-specific PET imaging scanner. With these studies they were able to evaluate both the effect on NEC rates and lesion detectability and demonstrated that properly designed sparse septa can improve lesion detection over the traditional 2D or fully-3D configurations. In our study we focus on NEC rates for different effective patient diameters, as our previous studies [14] have shown that lesion detection is closely related to NEC density, if all other parameters are kept constant.

The Discovery STE was first modeled with the SimSET Monte Carlo simulation package [15]. Following results from previous investigations on the GE Advance PET scanner [16], we modeled partial collimation modes that used one-half (2.5D) and one-third (2.7D) the usual number of septa. These collimators were then built and installed on the DSTE scanner. NEC was measured in 2D, 2.7D, and 3D for the NEMA NU2-2001 count-rate cylinder, and similar cylinders of larger diameter.

We also present preliminary imaging results with the partial collimation mode. Partial collimation introduces an unusual sensitivity pattern with both in-plane and oblique-angle dependence. Methods to account for the sensitivity pattern were incorporated into the 3D iterative image reconstruction process.

II. Materials and Methods

A. DSTE PET Scanner

A Discovery STE PET/CT scanner was installed at the University of Washington in September 2005. The DSTE PET scanner is a 24-ring Bismuth Germinate (BGO) system with 15.7 cm axial field of view (FOV) and 70 cm transaxial FOV. There are 560 BGO crystals in each ring. Individual BGO crystals are 4.7 mm × 6.3 mm × 30 mm (tangential ×

axial $\times$ radial). The DSTE is equipped with a conventional collimator that contains 23 tungsten septa, one between each of the 24 detector rings, plus end-shielding. The septa are 5.4 cm deep, and 0.8 mm thick. In addition to this conventional (2D) collimator, two specialized partial collimators were constructed for the DSTE. The two partial collimators had the same geometry as the conventional 2D collimator, but with only 11 septa (2.5D), and seven septa (2.7D). Fig. 1 shows the orientation of the septa for each case where septa are present. (In 3D the end-shielding is in place, but there are no septa.)

B. SimSET Monte Carlo Simulation

We modeled DSTE system count rates with SimSET in 2D, 2.5D, 2.7D, and 3D modes. True and scattered coincidence events were binned according to the DSTE scanner geometry from one SimSET run. To estimate randoms rates we ran SimSET in ‘SPECT’ mode, i.e., tracking single photons instead of coincidence pairs. This gave us an estimation of the detected singles events, from which we calculated random events.

The PET scintillation crystal is modeled as a solid annulus of BGO in SimSET. This differs from the scanner construction, which employs block detectors [17]. As such, it was necessary to correct the SimSET output by a packing-fraction factor representing the difference in BGO volume of the solid annulus and the actual volume of BGO in the DSTE scanner. Block detector modeling is currently being implemented in SimSET [18], but this new block version of SimSET was not used here. Another correction made to the SimSET output was for live-time effects experienced on the scanner, but not modeled by SimSET. Live-time vs. activity/count-rate measured for 2D and 3D modes were normalized to single-photon flux incident on the BGO, then applied to 2.5D and 2.7D results generated with SimSET.

The new version of SimSET that models block detectors will be able to account for detector variations that were not incorporated into the results presented here, including energy resolution and sensitivity variations between crystals in the center of the block and at the edge of the block. These effects likely contribute to differences observed between simulated and measured results, as described below.

C. Count-Rate Phantoms

The NEMA-specified count rate measurement uses a 20 cm diameter, 70 cm long polyethylene cylinder that is solid except for a 3 mm hole along its length and 4.5 cm from the axis of the cylinder. A line source is inserted into this hole and count rates are measured over time as the source activity decays.

The NEMA count rate measurements were expanded to include larger cylinders that more accurately represent typical sizes of patients in North America. NEMA-style count rate measurements were repeated with a 27 cm diameter cylinder, and a 35 cm diameter cylinder. In each case, the cylinders were still 70 cm long, and the same source activity and position was used, i.e., the source was still a 70 cm long, 3 mm diameter line source displaced 4.5 cm from the cylinder axis.

D. Scanner Measurements

The NEMA NU2-2001 protocols were followed for conventional 2D and 3D count-rate/scatter-fraction measurements on the DSTE in the University of Washington Radiology Department. We then removed the 2D collimator and replaced it with the 2.7D collimator. The NU2-2001 protocol was then followed for this new configuration. In addition to the count-rate cylinder, we imaged a NEMA IEC Body Phantom (Data Spectrum Corp.) in order to begin investigating image reconstruction methods for the partial collimation acquisition

mode. The phantom contains 4 hot spheres (inner diameter (ID, mm) = 10, 13, 17, 22), 2 cold spheres (ID(mm) = 28, 37), and a cold cylinder in the center (51 mm dia.). A large uniform sheet source was also imaged to investigate normalization.

III. RESULTS

A. SimSET Monte Carlo Simulations

The number of T, R, S, and NEC counts generated in SimSET for each collimation are shown in Fig. 2 as a function of activity in the 20 cm diameter NEMA count-rate phantom.

Most notable in Fig. 2 is the NEC in the activity range between ~ 5 mCi and 20 mCi, where the partial collimation NEC is significantly above that of 2D and 3D.

Fig. 3 shows the NEC curves for 2D, 2.7D, and 3D when the larger phantoms were used. (The 2.5D case is omitted for clarity on the graph; 2.5D NEC follows the trends expected from Figs. 2 and 3.)

B. Measured Count Rates

The 2D, 2.7D, and 3D count rate curves measured on the DSTE PET scanner using the 20 cm diameter cylinder are shown in Fig. 4.

The measured results comparing count-rates versus cylinder diameter are shown in Fig. 5. Only the results for the 2.7D collimation are shown. The trends seen for 2.7D were followed in results for other collimation schemes.

As expected, larger cylinder phantoms reduce the NEC. This is of interest because the average size of patients (in North America) tends to be larger than what a 20 cm diameter cylinder represents. To find the optimized scanning protocol that maximizes NEC we must pay attention to the count-rates for larger objects. The activity value that maximizes NEC is slightly lower for the larger objects.

A result that is perhaps not intuitive initially is that the number of scattered events is roughly the same for the 20 cm diameter cylinder and the 27 cm diameter cylinder (Fig. 5(c)). This can be explained by the fact that, while the number of scattered photons increases with increased phantom size, the number being attenuated also increases. The balance between scatter and attenuation in a 20 cm cylinder and 27 cm cylinder equalizes the overall number of scattered photons emerging from the phantoms.

The relative fraction of scattered events increases in the larger phantoms. Table 1 lists the scatter fraction, sf , for the different size phantoms and different collimators, from both measured and simulated results.

$$sf = S / (T + S)$$

C. Image Reconstruction

Partial collimation introduces unusual sensitivity patterns that vary both in-plane and with oblique angle. We derived a sensitivity correction factor from measurements of a planar sheet source. The sheet source correction was incorporated into the model-based normalization of the system matrix in an ordered-subsets expectation maximization (OSEM) reconstruction. The correction method was tested on the image quality Body Phantom. Fig. 6 shows the resulting images with and without use of the custom 2.7D normalization.

A selected sagittal slice of the Body Phantom image for each reconstruction method is shown in Fig. 7. The improved inter-plane uniformity is clearly seen in the image reconstructed with the 2.7D normalization. A profile through one of the hot spheres in these images is also shown in Fig. 7. The profile shows better peak height from the 2.7D-corrected image and less noise in the baseline.

IV. Discussion & Conclusions

Partial collimation of PET detectors offers benefits over both 2D and 3D acquisition: random events are substantially reduced compared to 3D without the large loss of true event sensitivity seen in 2D. These advantages were borne out over a range of object sizes and for activity ranges relevant to clinical PET scanning. A PET scanner with fixed partial collimation may therefore be a better option for a system without retractable septa than PET systems that operate in 3D mode only.

Higher NEC in the 5–20 mCi range was measured with partial collimation. Partial collimation therefore stands to improve the statistical quality of many standard patients scans. In the future we will continue this evaluation through both simulations and measurements using objects with more anthropomorphic activity distributions than the cylindrical phantoms used here.

Except for a global scaling factor, the simulation predicted the relative count rates very well; relative differences between the measured peak count rates and the activity values at which the peaks occur followed the simulation results closely. The discrepancy in absolute counts is attributable in part to the absence of block detector modeling in the version of SimSET used in this work, and the omission of the patient bed in our SimSET model.

A preliminary investigation into image reconstruction with partially collimated datasets showed very encouraging results. The unusual sensitivity pattern cast by the partial collimation can be accounted for with specialized normalization incorporated into the reconstruction system model. Work is continuing on appropriate scatter correction and optimized normalization algorithms, as well as other geometric configurations.

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Fig. 1.
Placement of the septa in partial collimation modes.

Fig. 2. SimSET: (a) Trues, (b) Randoms, (c) Scattered, (d) NEC count rates vs. activity in the 20 cm diameter NEMA count-rate cylinder phantom for each collimator.

Fig. 3. NEC rates from SimSET in 2D (black), 2.7D (blue), and 3D (red). NEC is reduced overall for larger phantom diameters (cf. Fig. 2(d)), but the relative advantage of 2.7D is maintained.

Fig. 4.

Count-rates measured on the DSTE PET scanner: (a) Trues, (b) Randoms, (c) Scattered, (d) NEC. The measured rates followed the predictions by SimSET (Fig. 2) in relative distributions. SimSET overestimated NEC by 40%–50% for 2D, 2.7D, and 3D. Most importantly, the measured 2.7D NEC showed the advantage predicted by SimSET in the clinically relevant activity range of ~ 5 – 20 mCi.

Fig. 5. Measured count-rates using the 2.7D collimation and different cylinder sizes: (a) Trues, (b) Randoms, (c) Scattered, (d) NEC. Phantom size reduces the trues and NEC in a predictable manner. Randoms and scattered events tend to equalize for the different sized phantoms due to the competing effects of increased scattering and increased attenuation in the larger object.

Fig. 6. Axial views of the Body Phantom. Reconstruction was performed with 3D OSEM. (a) Images without correction for the 2.7D sensitivity patterns. Plane-to-plane variations are due to improper normalization. (b) Images reconstructed using the 2.7D sensitivity correction. The inter-plane variations are greatly reduced.

Fig. 7. Sagittal view of the Body Phantom: TOP LEFT: Reconstructed without compensating for the 2.7D sensitivity pattern. BOTTOM LEFT: Reconstructed with 2.7D normalization. RIGHT: Profile through the hot sphere as indicated by the red dashed lines on the images at left. Applying the 2.7D normalization improves the image uniformity/reduces the baseline noise in the profile, as well as increasing the peak height of the profile through the hot sphere.

Table 1

Scatter Fraction derived from measurements and simulations

	2D		2.7D		3D	
	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
20 cm	20.3	16.8	29.0	26.0	33.7	33.5
27 cm	*	17.7	38.9	35.7	45.3	42.6
35 cm	*	25.3	46.6	45.7	54.8	53.3

* measurements in progress